

Lunar Reconnaissance Orbiter (LRO) Rapid Thermal Design Development

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ABSTRACT

The Lunar Reconnaissance Orbiter (LRO) project had a rapid development schedule starting with project conception in spring of 2004, instrument and launch vehicle selection late in 2005 and then launch in early 2009. The lunar thermal environment is one of the harshest in our solar system with the heavy infrared loading of the moon due to low albedo, lack of lunar atmosphere, and low effective regolith conduction. This set of constraints required a thermal design which maximized performance (minimized radiator area and cold control heater power) and minimized thermal hardware build at the orbiter level (blanketing, and heater service).

The orbiter design located most of the avionics on an isothermalized heat pipe panel called the IsoThermal Panel (ITP). The ITP was coupled by dual bore heat pipes to an Optical Solar Reflector (OSR) covered heat pipe radiator. By coupling all of the avionics to one system, the hardware was simplified. The seven instruments were mainly heritage instruments which resulted in their desired radiators being located by their heritage design. This minimized instrument redesigns and therefore allowed them to be delivered earlier, though it resulted in a more complex orbiter level blanket and heater service design. Three of the instruments were mounted on a tight pointing M55J optical bench that needed to be covered in heaters to maintain pointing. Two were mounted to spacecraft controlled radiators. One was mounted to the ITP Dual Bores. The last was mounted directly to the bus structure on the moon facing panel. The propulsion system utilized four-20 pound insertion thrusters and eight-5 pound attitude control thrusters (ACS) in addition to 1000 kg of fuel in two large tanks. The propulsion system had a heater cylinder and a heated mounting deck for the insertion thrusters which coupled most of the propulsion design together simplifying the heater design. The High Gain Antenna System (HGAS) and Solar Array System (SAS) used dual axis actuator gimbal systems. HGAS required additional boom heaters to cool the ~10 W of RF losses thru the rotary joints and wave guides from the 40 W Ka system. By design this module needed a fair amount of heater, blanketing, and radiator complexity. The SAS system required a separate cable wrap radiator to help cool the Solar Array harness which dissipated 30 W thru the actuators and cable wraps. This module also was complex.

INTRODUCTION

Lunar Reconnaissance Orbiter (LRO) will be launch in June 2009 on an Atlas V into a direct insertion trajectory to the moon. LRO is Co-manifested with LCROSS lunar impacter mission. On-board propulsion system will be used to capture at the moon, insert into and maintain 50 km mean altitude circular polar reconnaissance orbit. 1 year Exploration mission will be followed by up to 3 year Science mission. Orbiter is a 3-axis stabilized, nadir pointed spacecraft designed to operate continuously during the primary mission. Investigation data products delivered to Planetary Data Systems (PDS) within 6 months of primary mission completion.

OVERALL THERMAL DESIGN PHILOSOPHY

Thermal is a schedule backloaded subsystem that can be a major schedule driver during Integration and Test (I&T) phase of the mission. Often what is an ideal thermal design requires extensive analysis and critical path hardware builds and or can be difficult to test at a system level. Spending more money on thermal hardware that can be qualified early and simplifies I&T generally saves money in the end. This is because I&T's standing army is so costly and thermal hardware is still relatively cheap. Under sizing thermal vastly increases analytical effort and complicates testing as does having separate heater and radiator combinations for every heat source. Bundling heat sources into one thermal control system also mitigates the risk of any one component will change thermal dissipation requirements late in the thermal development to drive its temperature out of limits.

Thermal margins tend to be some of the most narrow amongst satellite subsystems and having lots of components or heater sizes close to limits costs more schedule and therefore cost in the end when things need to be fixed and re-tested or incur risk with last minute waivers.

The LRO thermal design followed these general guidelines as closely as feasible:

- a) Modularize the design so that the thermal hardware build can occur in parallel with each module housed in different locations. Ideally much of the assembling work can be done out of house as not to compete with the rest of the project's technician needs. Test them at the module level to minimize orbiter level risk. This principle is best observed by the relative decoupling of the Instrument Module, Propulsion, and HGAS from the avionics and bus.
- b) Minimize numbers of radiators, thermal interfaces, and blanketing work so that the thermal can be analyzed, designed, manufactured, built, and tested as simply as possible. The avionics and battery radiators are probably the best examples.
- c) Provide clear field of views for radiators and point them in the optimum direction even if this means re-doing the mechanical design. Analytically this type of radiator is easiest to predict and becomes independent of the late developing blanket design and therefore minimizes thermal model complexity and detail requirements. The avionics and battery radiators are probably the best examples.
- d) Maximize conductive path to radiator minimizing variability by reducing sensitivity to blankets and interface conductances. Utilize highly conductive heat pipes to minimize temperature losses. This makes the model less sensitive to workmanship variations. The avionics design is probably the best example.
- e) Thermally link similar requirement components (avionics) together. This allows greater thermal mass and therefore less sensitivity to power or thermal environmental or design and development transience.
- f) Thermal designs should not rely on unfilled spaces in the mechanical model to radiator heat. Often mechanical designs are empty of details until CDR, and the addition of details may require re-design later when the space becomes filled with harnesses and connectors or larger than expected boxes. This also allows the design to be simple in appearance and radiator sizing can be checked with a simple hand calculation, rather than relying on radk calculations.
- g) Make sure the system has adequate power switching capability above and beyond current predicts to allow for inefficiencies in the heater hardware builds and to accommodate voltage swings. As the thermal analysis is often in flux well beyond CDR, erring on the side of larger heaters generally is not problematic and creates a more forgiving thermal design.
- h) Harnesses carrying high amperages such as solar arrays and high power RF systems generally have large amounts of power losses that aren't always specified to thermal systems. Make sure power losses and harness lengths are understood and that the thermal design can handle the dissipated power.
- i) All flight systems are ultimately designed to be operated in the harsh space environment. Ensure that the thermal system fails safe and has enough alternative options so no one part of it can

result in the loss of the mission. Thermal redundancy is typically easy to implement and is of paramount importance in the case of anomalous conditions that are commonly happen once or twice in a mission. All of the mission critical heaters were redundant as were the heat pipes.

LUNAR THERMAL ENVIRONMENT

Figure 1 shows the modeling of the lunar thermal environment. The environmental assumptions are in Table 1.

$$q''_{IR} = [(C_1 - C_2) \cdot \cos(\beta) \cdot \cos(\theta)]$$

where:

- q''_{IR} = IR flux from Lunar surface
 C_1 = Peak flux at subsolar point
 C_2 = Minimum flux emitted from shaded Lunar surface

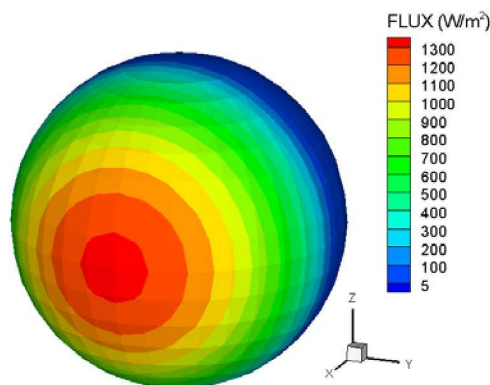


Figure 1 – Lunar IR environment

	Hot	Cold
Solar	1420 W/m ²	1280 W/m ²
Albedo Factor	0.13	0.06
IR (at subsolar C1)	1420 x (1 - 0.06) = 1335 W/m ²	1280 x (1 - 0.13) = 1114 W/m ²
IR (Cold side C2)	5 W/m ²	5 W/m ²

Table 2 – Lunar Design Parameters

LRO was designed such that the entire backside of the moon is emitting at the C2 flux. LRO is flying a NS43C (white) painted calorimeter and a MSA94B (black) painted calorimeter that will be pointed nadir for the duration of the mission which will measure orbital variations during the LRO mission.

AVIONICS THERMAL DESIGN

The avionics thermal design utilizes an embedded heat pipe panel that is single fault tolerant, 1-g testable and optimized for thermal and schedule performance. Figure 2 shows the heat pipe network of the heat pipes. Figure 3 shows how the avionics module is coupled to the embedded heat pipe radiator via 2 dual bore heat pipes. Figure 4 shows the avionics radiator heat pipes layout. Figure 5a shows the as-built avionics module and Figure 5b shows the as-built radiator.



Figure 2 – Heat Pipe Layout of Avionics Module

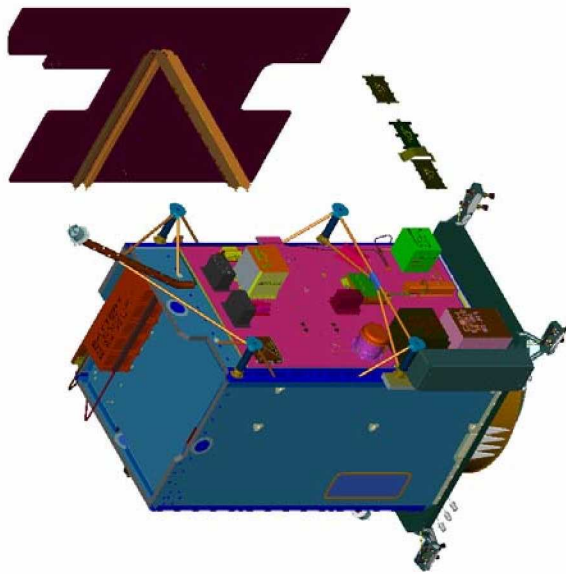


Figure 3 – Dual Bore Heat Pipes Coupling the Avionics panel to the radiator

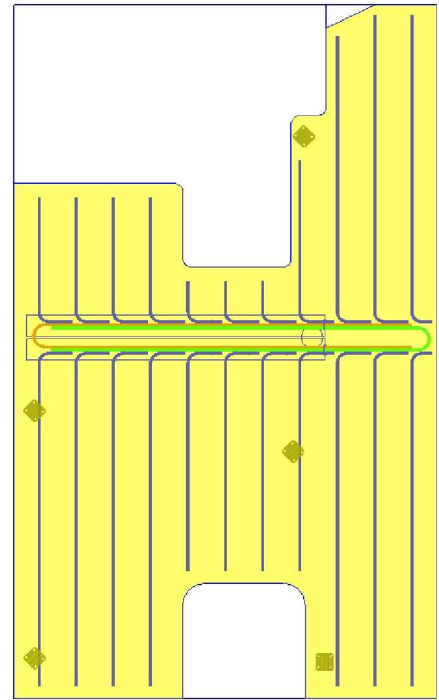


Figure 4 Avionics Radiator Layout



Figure 5a Avionics Module As-Built



Figure 5b – Radiator As-built

As is noticed from Figure 5a, most of the avionics module between the boxes has been filled with harness. Without the ability to co-locate all boxes on a single panel, the harness requirements and weight would be vastly increased. Coupling all of the boxes on a heat pipe panel allowed individual box powers to change without invalidating radiator and heater sizing and would allow post bonded inserts to add additional boxes.

On the launch vehicle and during I&T, Figure 2 was rotated clockwise 90 degrees. The highest power boxes were located at the bottom of the heater pipes which allowed their power dissipation to be conducted in reflux onto the avionics radiator and convected into the room. This eliminated the need for ground cooling loops. Care was taken in locating the top most mounted pipes (above the dual bore) so they did not need to rely on the heat pipe network in I&T (as it would not work in the I&T orientation). The long horizontal legs of each heat pipe ensured that there were no 1-g startup heat pipe conductance issues as the lower horizontal lengths were stratified with ammonia liquid and vapor.

The savings in I&T by integrating all of the avionics into a single panel is clear when the complexity of heater circuits and blankets can be reduced to one radiator sizing blanket and one operational and one survival heater circuit for the heat pipe network. The modularity of having the avionics altogether allows the propulsion and instrument module to be built separately.

The testing of the avionics module was performed separately from the radiator. This testing allowed us to modify some of the interface materials for easier integration as the overall heat pipe network was more conductive than baselined. Testing early allowed LRO to reduce thermocouple allocation for the panel and radiator and reduces overall risk to the project by validating a major portion of the orbiter thermal model prior to orbiter level thermal testing.

Comparing this design to the philosophy in section 2, the avionics design was modular (could and was tested separately), minimized radiators as much as possible (avionics and battery were separate), radiators had a clear field of view, designs were highly conductive and highly coupled across avionics, had two sets of heaters (Large software controlled for pre-heating, and smaller essential heater bus heaters), and had redundancy built into the heaters and heat pipes for failure tolerance.

INSTRUMENT BENCH THERMAL DESIGN

The instrument bench was located on the opposite side of the orbiter from the avionics to help balance mass properties. The instrument bench had tight pointing requirements (1 arc minute) between the Star Trackers and the LROC and LOLA instruments. This resulted in a minimum to maximum operational temperature range of 0 to 30 C and a M55J mechanical structure. The thermal complexity for the instrument module was maintaining the temperature requirements for the bench over an extreme thermal environment. M55J has almost 7 times lower thermal conductivity versus aluminum. LRO spread the heat using about 25 operational heater circuits utilizing aluminum tape. 2 to 3 layers of 3 mil aluminum tape was required to keep the bench relatively isothermal. As the bench heaters were being applied to a low conductivity surface, heaters had to be fairly small in size so that they wouldn't develop gradients due to uneven heating of the bench, greatly increasing the number of heaters. The hardware build effort took months. See Figure 6 for the as-built optical bench with heaters exposed and Figure 7 for showing the complexity of the blanket build. As multiple instruments also utilized their own radiators, the blanket design was further complicated by the requirement to provide clear fields of views for the radiators while maintaining thermal isolation on the bench. Canyon blankets were also added to the zenith surface to minimize solar entrapment in low Beta angles.

The instrument module design compromised on many of the ideals in Section 2. This was due to the desire to minimize mass (no separate metal shell over which would have decreased the number of bench heaters), and since the instruments were heritage, many had their own radiator designs. This greatly increased the heater and blanketing scope of work but was necessary programmatically. The design intended to keep field of views of radiators clear, though sometimes harnessing with the heritage designs got in the way such as on the Star Trackers and LAMP. Redundancy is roughly achieved by having operational and survival heaters. All instruments work at survival temperatures and operational heaters plus an operating instrument are enough to keep instruments from freezing. There are 8 software controlled heaters on the optical bench with adjustable setpoints to help steer the bench if instrument pointing is not per what is required in the mission.



Figure 6 Optical Bench Heaters with aluminum tape



Figure 7 LRO Optical Bench Tailored blankets

HGAS THERMAL DESIGN

HGAS (High Gain Antenna System) was unique in that in order to meet the mission communications demands, LRO used a 40 W Ka RF system. Ka band loses approximately 50% of its energy from the amplifier exit until it is transmitted from the dish. As the dish had to have a view of the earth at all times and the mission wanted to remain nadir pointing during communication passes, the antenna required a dual axis gimbal system on a very long boom to clear the solar array. Figure 8 shows the complexity of the mechanical build. As the various heat sources could not be well coupled across the rotational joints,

multiple radiator and heater sets had to be implemented. This resulted in tricky detailed thermal analysis and highly complex blanket design (~40 separate blankets) to prevent radiator blockage and reliable rotation about the actuator axes without the potential for blanket interference. As the actuators were made of titanium and the software required both actuators to be always enabled and powered, aluminum tape was used to couple the heat sources in the actuators to their larger coaxial cylindrical radiators.

The HGAS design was designed to be thermally separate TCS from the spacecraft which allowed separate analysis and testing. This simplified the orbiter level testing as thermal sinks were not required. Redundant heaters were on all of the rotating components.

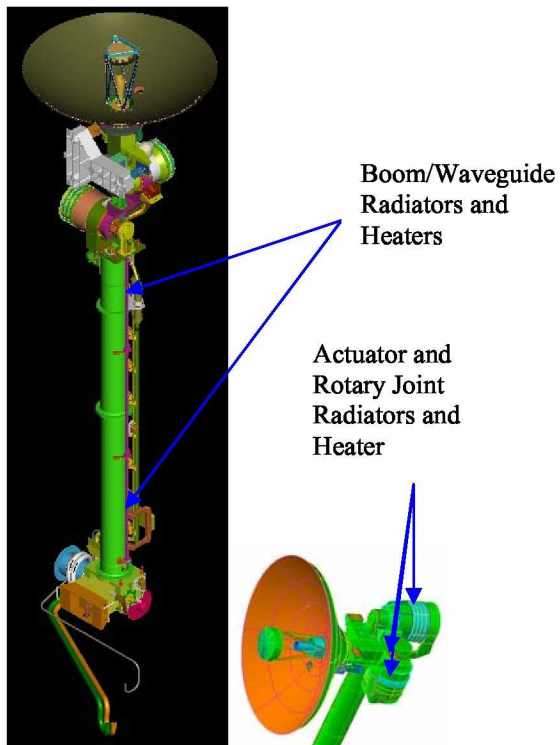


Figure 8 HGAS Thermal Design

PROPULSION THERMAL DESIGN

The propulsion design is integrally coupled to the base of the spacecraft. The upper tank is thermally coupled to a central cylinder which also couples to the bottom deck and lower tank. Large heaters were used on the cylinder to provide a benign temperature for the tank interfaces and lines on and inside the cylinder see Figure 9. The titanium tanks were covered in low density heaters and overtaped 2-3 times with 3 mil aluminum tape. The propulsion system was then radiatively isolated from the spacecraft with blanketing and a VDA double layer film on the upper tank.

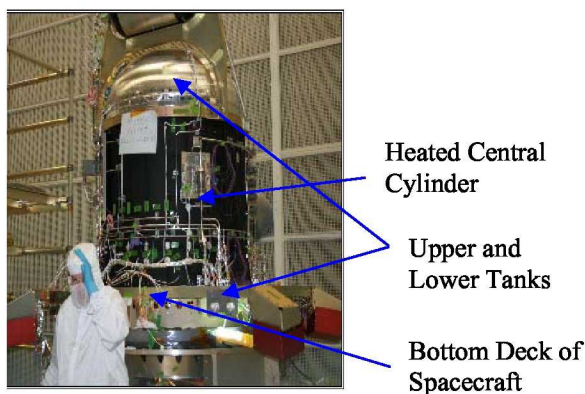


Figure 9 Unblanketed Propulsion System



SAS THERMAL DESIGN

The solar array design is dominated by a very hot array which is somewhat isolated from a dual axis gimbal system. During thermal vacuum testing, it was noted that the harness dissipation was much larger than anticipated. This required modifications to the hardware late. The harness dissipation was 6 times higher than the actuator power (~40 W compared to about 6-7 W). Figure 11 shows the flight SAS gimbal assembly. Each actuator and the outer cable wrap had its own heater and thermostat. Aluminum clamshell design was used to couple the actuators to their radiators. About 20 blankets were required to temperature control the actuator. Figure 12 shows the full array.

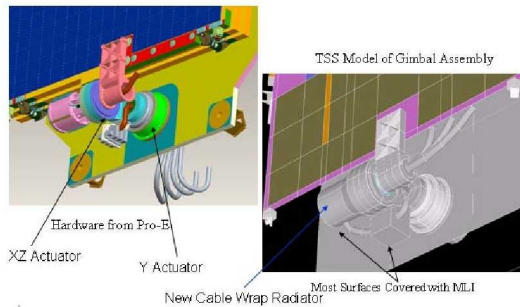


Figure 11 – Solar Array Gimbal



Figure 12 – Full Solar Array

The discovery of the large harness dissipations resulted in the necessity to thermally couple the harness and cable wrap to the interior of the avionics module. Redundancy in the heaters makes the system robust. Analytically, like HGAS, this system is detail intensive and therefore required a high degree of analysis effort to capture the radiator fields of view and correctly model the array. Likewise, this design was very complex in blanket, radiator, and heater design. This was necessitated in fixing the late harness dissipation issue and the poor conduction across the rotating joints.

CONCLUSIONS

LRO as a spacecraft has a large amount of complex modules: 2 deployables with dual axis gimbal systems and high dissipation (RF or harness losses), 4 thermally isolated instruments, 3 instruments with spacecraft controlled interfaces, large propulsion system with 12 thrusters, and the complex thermal environment around the moon. LRO thermal tried to optimize the thermal design to minimize analytical and hardware build complexity, but programmatic and configuration complexity drove the design in the direction shown. Optimization in future missions should strive for coupling thermal control systems, thermal component redundancy and flexibility (software controlled heaters), and simplifying analysis and hardware builds as much as allowable. Orbiter level Integration and Test timesaving and risk reduction can never be underestimated. In the end this also minimizes analysis and blanket work, the two largest thermal costs.

ACRONYM LIST

Acronym	Description
ACS	Attitude Control System
CDR	Critical Design Review
Edge	Edge Space System
GSFC	Goddard Space Flight Center
HGAS	High Gain Antenna System
I&T	Integration and Test
IR	Infrared
ITP	IsoThermal Panel
LAMP	Lyman Alpha Mapping Project
LCROSS	Lunar Crater Observation

	and Sensing Satellite
LRO	Lunar Reconnaissance Orbiter
OSR	Optical Solar Reflector
PDS	Planetary Delivery System
RF	Radio Frequency
SAS	Solar Array System
Sigma	Sigma Space
TCS	Thermal Control System
VDA	Vapor Deposited Aluminum

REFERENCES